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PULSED HYDROJET PROPULSION

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ABSTRACT

The pulsed hydrojet is a device in which the water ingested from the free stream is accelerated out of the exhaust pipe to produce thrust. In this report we describe and analyze a way of accelerating the stream of water with pockets of high pressure steam and gas generated inside the stream by an exothermal reaction of suitable propellant injected and dispersed in the water. The velocity increment that must be imparted to the water to produce a substantial thrust need not be very large because the density of the water is comparable to the average density of the accelerated body. Results of the numerical modeling of the proposed jet acceleration mechanism indicate that the hydrojet propulsion device is potentially capable of propelling underwater projectiles at speeds three to five times greater than those currently attainable. Several promising applications of the hydrojet thruster are discussed and evaluated.

PULSED HYDROJET PROPULSION

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I. INTRODUCTION

In this report we describe and analyze a method of propelling underwater projectiles at speeds three to five times greater than those attainable with present propulsion systems. Such a high thrust propulsion system will have many applications and will satisfy many needs when developed successfully. We discuss three applications in some detail: (1) acceleration of small (10 cm dia, 100 cm long), massive (50 kg) underwater projectiles to velocities at which they act as kinetic energy penetrators; (2) propulsion of small subtorpedoes (carried on a standard torpedo employed as a bus) that may be used to deploy underwater anti-torpedo nets; and (3) provision of supplementary thrust to increase (double) the acceleration of present submarine-size vessels and/or provide capability for substantially higher (50%) speed during short time intervals (several minutes).

One way to concentrate high thrust in a small cross-sectional area is to ingest water from the free stream, accelerate it to a high velocity, and to expel the resulting water jet to the rear. The velocity increment that must be imparted to the water to produce high thrust need not be very large (a factor of 1.5 to 2.0) because the density of the water is comparable to the average density of the accelerated body. In the propulsion concept proposed in this paper the acceleration is accomplished by generating pockets of high pressure steam and gas inside the water jet; this increases the average specific volume and requires a higher average velocity to maintain mass conservation. The pockets of steam and gas are obtained from the exothermic reaction of a propellant (alkali metal in general, lithium in particular) with water. The propellant must be injected with dispersion that is sufficiently low to ensure that the reaction goes to completion in the required time interval but also sufficiently high to ensure local generation of high pressure steam and not global heating of the water. The modeling and optimization of the injection and dispersion ~~processes~~ of the propellant are subjects of a complementary study. Preliminary analysis of these processes did not uncover any fundamental reasons that would preclude the possibility of achieving the necessary energy deposition intensity.

The use of an alkali metal as the propellant has several advantages. First and foremost is the high energy density: the reaction of lithium with water liberates 31 kJ of heat per gram of Li as compared to only approximately 10 kJ per gram of alcohol-oxygen mixture. This is partly a consequence of using free water as one of the reactants. Another consequence of the exploitation of free water is the simplicity of the concept: it requires neither storage and carburation of the oxidizer nor an ignition system because the reaction $Li+H_2O$ occurs spontaneously at any temperature of interest. Therefore the engineering embodiment of the concept will contain very few moving parts.

The use of metal alloys as fuels for underwater propulsion, in general, and of alkali metals, in particular, has been investigated previously to a significant extent.[1,2] The principal aim of these studies was the development of high performance reactants that would generate superheated steam which could be expanded through a DeLaval nozzle to generate thrust. The use of gas pockets to accelerate water jets and thus generate thrust has been tried also; however, the gas was generated and compressed in standard combustors and compressors.[3,4]

We combine the two above approaches into a concept in which the pockets of steam and gas are generated inside the water jet to be accelerated in consequence of direct and controlled injection of an alkali metal fuel. We differ from previous studies also in the intended applications of the hydrojet thruster. We propose to use it mainly for short duration sprints and thereby alleviate materials, vibration, and guidance problems that may be encountered.

This report contains the initial results of intended extensive numerical studies of all aspects of the proposed concept and of the associated reacting flows. The results of this modeling will provide the information necessary for the planning of the experiments that would validate the concept. We expect that currently available numerical modeling capabilities will significantly reduce the uncertainties connected with the experimental investiations of two-phase reacting flows.

The presentation is organized as follows: In Sec. II we describe the concept and formulate the initial-boundary value problem for its modeling, in Sec. III we summarize very briefly the numerical code used to solve the governing system of equations and present the results, and in Sec. IV we describe several envisaged applications of the propulsion device.

In conclusion we outline the current and future research requirements in this area.

II. THE CONCEPT AND THE MODEL

We now sketch schematically the configuration of the hydrojet propulsion device and formulate the initial-boundary value problem that models its operation. The thruster is a hollow cylinder divided by a bulkhead into two parts. The forward part contains the propellant and its injection mechanism and the aft part is the reaction chamber with the water inlet ports and the exhaust pipe. The configuration is shown schematically in Fig. 1 with the water inlet scoops closed to accommodate possible launch tube constraints and open for normal operation. The presence of the flapper valves is symbolic; in an engineering realization of the device other types of valves, more suitable for heavy duty, may have to be used.

During operations at high speeds (exceeding 50 to 100 m/s) the flow will cavitate at the nose of the projectile and the cavity may not close upstream of the inlet scoops. This must be taken into account in the layout of the high speed projectile configurations.

The propellant is injected and dispersed when the reaction chamber is filled with water. The ensuing chemical reaction generates high pressure steam and the water inlet valves are closed either by that pressure or mechanically. After the water is expelled from the reaction chamber through the exhaust pipe, the inlet valves are opened either by the dynamic pressure of the free stream or by a control mechanism and the cycle is repeated. The pulse frequency may be controlled by the rate at which the reaction chamber is filled with water provided the chemical reaction rate can be made sufficiently high with appropriate propellant dispersion. The proposed thruster is capable of dead start because of the relative high density and incompressibility of water; in this respect it is better than pulse- and ram-jets operating in the air.

We present the results of two calculations that illustrate the numerical modeling of the hydrojet operation. One is for a small (10 cm dia) projectile in which the propellant reaction zone may extend over the entire cross-sectional area. Several such projectiles may be carried on one standard torpedo and employed as kinetic energy penetrators (containing explosive charges for subsequent attack on the inner hull of double-hull vessels) or to deploy torpedo intercept nets as shown schematically in Fig. 2. The second computation presented is for a large (50 cm dia) thruster in which the reaction zone does not extend to the wall of the cylinder. Such configuration alleviates the materials problems; it may be used as a primary or auxiliary propulsion system (for the terminal dash to the target) on standard torpedoes or in a battery of auxiliary propulsion units intended to increase the acceleration and speed of submarine-size vessels during short sprints.

The cylindrical computational region is illustrated in Fig. 3 where the propulsion device occupies the upper left hand corner. The water inlet boundary is on the left hand side; the inlet area A_1 is specified to be an arbitrary fraction of the total number of computational cells contained in the radius. The maximum inlet velocity is prescribed for each run. Along the rigid cylindrical boundaries the flow is tangential. On the right hand the jet exhausts into a large cylindrical tank; on its downstream end the pressure is maintained at a prescribed value. The tank is necessary to make the numerical problem well posed; because large pockets of steam and water emerge alternately from the exhaust pipe, the boundary condition there is unsteady and unknown a priori. The presence of the tank also makes it possible to determine the interaction of the exhaust jet with the free stream.

The computation proceeds as follows. Initially, the pressure, temperature, and velocity everywhere are set equal to the prescribed values, usually the free stream conditions, and the water inlet area is closed. At $t = 0$ the energy is added to the water in the shaded region at a specified rate (1 to 50 $kJ/cm^3/s$). When most (95%) of the water is converted into steam the energy deposition is terminated, the inflow boundary is opened, the inflow velocity is built up gradually (5% to 10% per time step) to its maximum value and maintained constant until the energy deposition region is refilled with water. At that time the inflow boundary is closed and the energy deposition is reinitiated to start the next cycle.

Clearly, this computational procedure does not model the effects of convection during the time of the chemical reaction, i.e., it assumes that the reaction occurs instantaneously. The determination of the actual reaction rate and its coupling to the flow are subjects of a separate study; the results will be incorporated into the hydrodynamic modeling when they become available.

The computation in which the initial and the free stream velocities are equal models the steady-state operation of the device. To model the transient behavior correctly requires integration of Newton's first law, $F = Ma$, in which the force F is the difference between the thrust, T, and the drag, D. Because the drag is proportional to the square of the velocity (approximately), this equation is nonlinear and must be integrated numerically together with the equations that govern the performance of the thruster. We have not done that yet; however, an approximate analysis of the transient performance with the assumption of a constant thrust will be described in a later section.

III. NUMERICAL RESULTS

The transient, two-dimensional (axisymmetric), two-phase flow associated with the pulsed hydrojet propulsion described in the previous section is determined with the computer code K-FIX[5] that was developed at LANL for nuclear reactor safety studies. The code numerically integrates the equations expressing the conservation of mass, momentum, and energy for the two phases; these eight equations are coupled through the exchange of mass, momentum, and energy. The differential equations are approximated with finite difference equations on an Eulerian grid; the approximations couple implicitly the rate of phase transition, momentum, and energy with pressure, density, and velocity fields. The explicit solution is obtained by iterations without linearization. The equation of state and the phase transition rates are approximated with analytic expressions.

In its original form the K-FIX code did not admit energy addition to the flow. A subroutine accomplishing this has been added for the purpose of the present study.

We present two results to illustrate qualitatively the nature of the flow associated with the hydrojet propulsion. Figure 4 is a plot of the contours of constant void fraction for the flow inside and aft of a 50-cm-diam thruster in which the chemical reaction region does not extend to the cylinder wall. High void fraction corresponds to steam pockets, therefore Fig. 4 shows the flow field after the third energy addition cycle has been completed.

Of course, the details of the flow inside the thruster can be modeled with computations that do not include the dump tank provided they are not extended beyond the time when the first steam pocket reaches the end of the exhaust pipe. In that case the computations require much less computer time and memory, therefore they should be utilized whenever possible. A representative result of a short duration modeling is shown in Fig. 5.

In the present study of primary interest are the impulse and the average sustained thrust developed by the propulsion device. These quantities are calculated from the histogram of the instantaneous thrust which is the difference of the total momentum flux out of and into the device. The total momentum flux is obtained by integrating the local flux over the cross-sectional area.

The instantaneous thrust generated by the 10-cm-diam device is shown in Fig. 6; it is negative when the inlet ports are open indicating that more momentum flows into the device than out of it. One of the objectives of future parametric studies should be the search for ways to reduce the area between the negative loops and the zero thrust line. The instantaneous thrust appears to vary somewhat irregularly because of the very high intensity of the energy deposition rate. In this calculation the intensity of the energy source was equal to 44.2 $kJ/cm^3/s$ and energy deposition region extended over 226.2 cm^3. When the energy source intensity is reduced to a value below 10 $kJ/cm^3/s$ the pulses become quite reproducible.

As mentioned previously, the energy source is turned on and off by a representative value of the void fraction in the energy deposition region, therefore the calculation of the total thermal energy input requires a summation subroutine which we have not yet implemented. The plot in Fig. 6 appears to indicate that the source is on during half the time; in that case the power input will be 5 MWt. The reaction of water with lithium liberates 31 kJ/g of lithium, therefore the propellant flow rate could be 161.3 g/s.

The impulse, calculated as the time integral of the instantaneous thrust, is shown in Fig. 7. The impulse oscillates, however, its average value appears to increase linearly after the initial transient; this indicates that the average thrust settled to a constant value. The plot of the average thrust, shown in Fig. 8, confirms that. The large initial value of the thrust indicates the dead start capability. (Throughout this report 1 ton designates a force of 10^9 dynes.)

The corresponding results for the 50-cm-diam propulsion device are shown in Figs. 9, 10, and 11. In these computations the intensity of the energy source had the value of 6.93 kJ/cm/s and the energy deposition region extended over 11.545 x 10^3 cm^3. The pulses of the instantaneous thrust are reproducible because of the much lower intensity of the energy deposition. Also the area between the negative loops and the zero thrust line is much smaller. If the energy source is on during half the time, then the power input would be 40 MWt and the corresponding lithium flow rate would be 1.29 kg/s.

The results presented in Figs. 6 through 11 were obtained with exploratory computations that did not include attempts to maximize the thrust or to minimize the propellant consumption. Therefore they do not indicate the full potential of the pulsed hydrojet propulsion. Nevertheless, the values of the thrust presented in Figs. 8 and 11 are not much below those that are needed to meet the performance requirements discussed in the next section.

We close this section with a comment about the energy deposition intensities. A stoichometric mixture of water and lithium requires 7/9 cm^3 of lithium for each cubic centimeter of water; therefore when that reaction supplies the energy, spacial energy density may be as high as 12 kJ/cm^3 of water. Consequently, the energy deposition source intensities used in our computations do not demand unreasonably high reaction rates.

IV. APPLICATIONS

In this section we estimate the capabilities of underwater projectiles and vessels propelled with the proposed thrusters and indicate some potential applications. The discussion is neither complete nor exhaustive, only illustrative.

The employment of small independently-propelled projectiles (SIPP) to intercept incoming torpedoes has been mentioned in Sec. II and shown schematically in Fig. 2. Aproximate estimates indicate that four 10-cm-diam projectiles and a 5-m by 5-m net can be stored inside the 12-in. torpedo and a 10-m by 10-m net inside the 21-in. torpedo. The net would be made of 1-cm-diam cables spaced 10 cm apart and deployed when the carrier torpedo is on an intercept trajectory with the incoming torpedo. Such a torpedo defense concept alleviates the guidance and detonation timing requirements needed to destroy the attacking torpedo by either impact or blast impulse.

Another promising application of SIPPs (Small Independently Propelled Projectiles) is as kinetic energy penetrators that contain explosive charge to attack the inner hull of double-hull vessels. The drag force acting on a 10-cm-diam projectile with a 30° half-angle conical nose is shown in Fig. 12; it is calculated with the drag coefficient applicable in the cavitating flow regime ($C_D = 0.4$ based on the cross-sectional area[6]). The result indicates that a thrust of 1 ton will propel the projectile at 80 m/s (160 knots) and that approximately 1.5 ton of thrust is required to attain a speed of 100 m/s (200 knots); the thrust value shown in Fig. 8 almost meets that requirement.

Results of approximate theoretical and experimental investigations of the deformation and penetration of thin plates by projectile impact indicate that a speed between 50 m/s and 100 m/s is sufficient to achieve penetration[7]. In this investigation the projectile length-to-diameter ratio was between 5 and 10 and the projectile diameter-to-plate-thickness ratio was between 4 and 8. Under these conditions the mode of failure is plugging or petaling in which the plate is sheared or torn rather than eroded as in hypervelocity impacts. In our proposed application the relative projectile and target characteristics will be the same as in the above study (10-cm-dia, 100-cm-long projectile, 1-cm to 2-cm thick outer hull plates) and we have confirmed the results of Ref. 7 with numerical calculations.

An arrangement of small projectiles inside the 12-in. torpedo envelope is shown in Fig. 13. An approximately equal number of 15-cm-diam, 150-cm-long projectiles can be accommodated inside the 21-in. torpedo; each of these would be capable of carrying approximately 23 kg (50 lb) of HE in addition to the propulsion and detonation systems. A warhead of this type would have the advantage of multiple hits and penetrations.

The derivation of estimates for the acceleration time and distance requires the analysis of the transient motion. The equation of motion for a floating or submerged propelled object is

$$M \frac{dv}{dt} = T - 1/2 \rho A C_D v^2 \tag{1}$$

where M is the mass, v the velocity, T the thrust, ρ the medium (water) density, C_D the drag coefficient associated with a reference area A, and t is time. For the purpose of this report sufficiently accurate results will be obtained with the assumption that the thrust and the drag coefficient remain constant during the motion. With this approximation Eq. (1) completely determines the performance of the projectile or vessel. Unfortunately it is a nonlinear differential equation that must be integrated numerically; we will present the results of such integration later.

Presently we derive an analytic approximation using the fact that the drag force is proportional to the square of the velocity, therefore its average value during the acceleration equals one-third of the value at the terminal velocity at which the drag force equals the thrust. With this approximation, Eq. (1) integrates to

$$v_t = \frac{2T}{3M} t_T \tag{2}$$

where t_T is the time required to accelerate to the terminal velocity v_T. Because the value of the terminal velocity is

$$v_T = \sqrt{\frac{2T}{\rho A C_D}}, \tag{3}$$

the acceleration time t_T is

$$t_T = \frac{3M}{\sqrt{2T\rho A C_D}}. \tag{4}$$

The representative values for a small projectile may be $M = 5 \times 10^4$ g (50 kg) $T = 10^9$ dyne (1 ton), $\rho = 1$ g/cm^3, $A = 78.54$ cm^2, $C_D = 0.4$, therefore $t_T = 0.6$ sec. Such transient duration is negligibly small on the time scale of underwater operations. The same value of t_T may be obtained using Eq. (2) with Fig. 12; however, Eq. (4) shows explicitly the dependence of the acceleration time, t_T, on the physical characteristics of the projectile.

The distance needed for the acceleration to the terminal velocity, t_T, is 24 m; this also is small relative to the range for which lithium propellant could be provided. That range can be as much as 1 km (1000 m) utilizing only between 1 ℓ and 2 ℓ (2000 cm^3) of storage volume for the lithium.

We now discuss the effect of thrust augmentation on the performance of submarine-size vessels and estimate the potential of hydrojet thrusters for that application. Results of the numerical integration of Eq. (1) for a vessel with M = 6000 ton, $C_D = 3.5 \times 10^{-3}$ and A_W (wetted area) = 3.5×10^7 cm^2 are shown in Fig. 14 for the four values of the thrust, 100, 150, 200 and 300 ton. The dashed vertical lines indicate the acceleration time obtained from Eq. (4) for the corresponding values of the thrust. These results show that the approximate Eq. (4) gives the value of the time required to reach 90% of the terminal velocity; such accuracy is sufficient for the purpose of this report.

Having established the validity of the approximate analysis we use it to determine the dependence of the average speed during the acceleration to terminal velocity on the available thrust. The magnitude of that speed may be used as a measure of the agility of the vessel.

For a motion induced by a constant force the average speed, v_a, equals one half of the final value; therefore, from Eq. (3)

$$v_a = \sqrt{\frac{T}{2\rho A C_D}} \ . \qquad (5)$$

Eqs. (3), (4), and (5) indicate that the performance and the agility of the vessel increase as the square root of the thrust. Therefore significant enhancement of these characteristics requires nearly doubling of the thrust.

The velocities of submarine-size vessels may range from 10 m/s to 20 m/s (20-40 knt), therefore the thrusts of their propulsion systems range approximately from 100 ton to 200 ton as shown in Fig. 14. The flow rate of alkali metal propellant (lithium) required to provide the average value (150 tons) of thrust is estimated in the following way. A force of 150 tons moving at an average velocity of 15 m/s dissipates energy at the rate of 22.5 MWt. Postulating that the conversion efficiency from thermal to propulsion energy is approximately 25%, the thermal power requirement is approximately 100 MWt. The reaction of lithium with water generates 31 kJ per gram of lithium, therefore the required lithium mass flow is 2.23 kg/s or 4.46 ℓ/s (the density of lithium is approximately 0.5). Consequently, provision of the additional 150 tons of thrust for 2 min. will require nearly 750 ℓ(3.5 55 gal. drums) of lithium. The effect will be acceleration to nearly 22 m/s (44 knt) in approximately 1 min. (acceleration distance ~660 m) and a dash of 1300 m (1500 yards) at that speed. If the thrust shown in Fig. 11 can be doubled with an appropriate choice of the operating parameters, then 10 to 15 50-cm-diameter thrusters would suffice to accomplish the above-indicated performance enhancement.

As mentioned earlier this discussion does not encompass all possible applications of the proposed hydrojet thrusters; it is intended to indicate the potential of these propulsion devices with examples of applications at the small and the large ends of the size scale. In the range of intermediate sizes these devices may be used to propel beach assult or river crossing boats (suggested by C. Schaniel of NWC). In that application the hydrojet thrusters have, in addition to compactness and high performance, the advantage of not needing a propeller which is prone to damage in very shallow water operations. Of course, thrust reversal capability will have to be provided to meet the maneuverability requirements.

V. SUMMARY OBSERVATIONS

In this report we have proposed and described a concept which, when developed, will result in a compact, high-performance hydrojet propulsion device. The potential of such thrusters have been illustrated with brief discussions of several possible applications.

We believe that the innovations inherent in our approach and outlined in this report will circumvent the difficulties that were the stumbling blocks in the previous attempts to develop similar concepts. The innovations are in the realization, analysis, engineering, and applications of the hydrojet concept.

We have carried out exploratory numerical calculations and obtained results that confirm the anticipated potential of the hydrojet propulsion. The computations include estimates of the performance requirements that the proposed concept must meet to merit the development.

Of course, the ultimate validation of the practicality and of the performance characteristics of most devices can be accomplished only with an experimental program, therefore future activities should be directed toward determination and specification of the relevant experiments. These efforts should encompass the following tasks:

1. Modifications of the hydrodynamic codes to better model the relevant physical phenomena;
2. Determinations of significant parameters and parametric trends;
3. Modeling and study of the propellant-water reaction rates;
4. Incorporation of the chemical reaction models into the hydrodynamic codes;
5. Engineering studies of system configurations, applications, and effectiveness.

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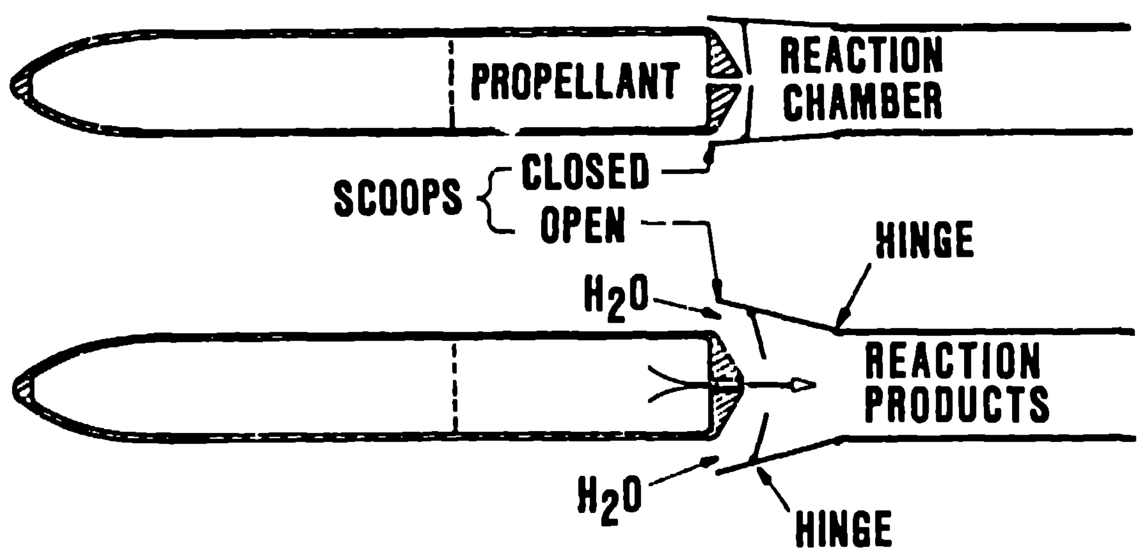


FIG. 1 PULSED HYDROJET THRUSTER
(SCHEMATIC)

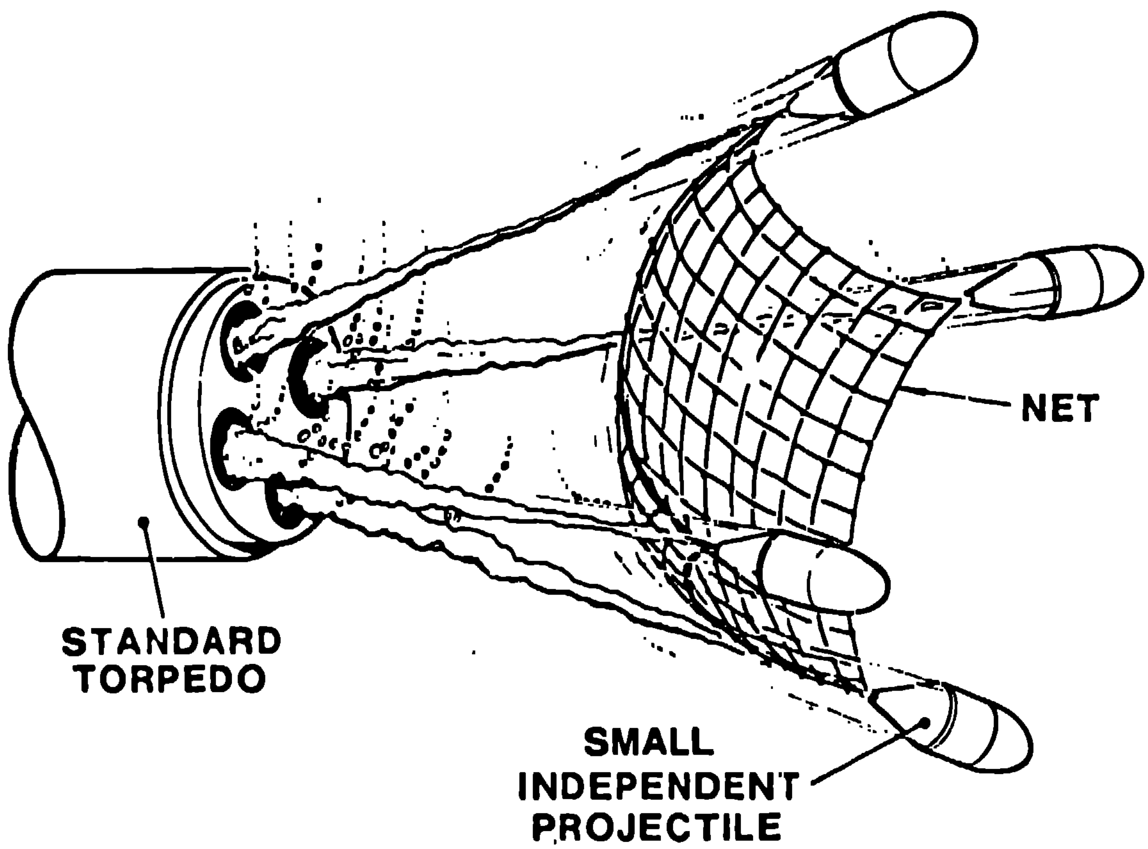


FIG. 2 TORPEDO INTERCEPT WITH SMALL INDEPENDENTLY PROPELLED PROJECTILES

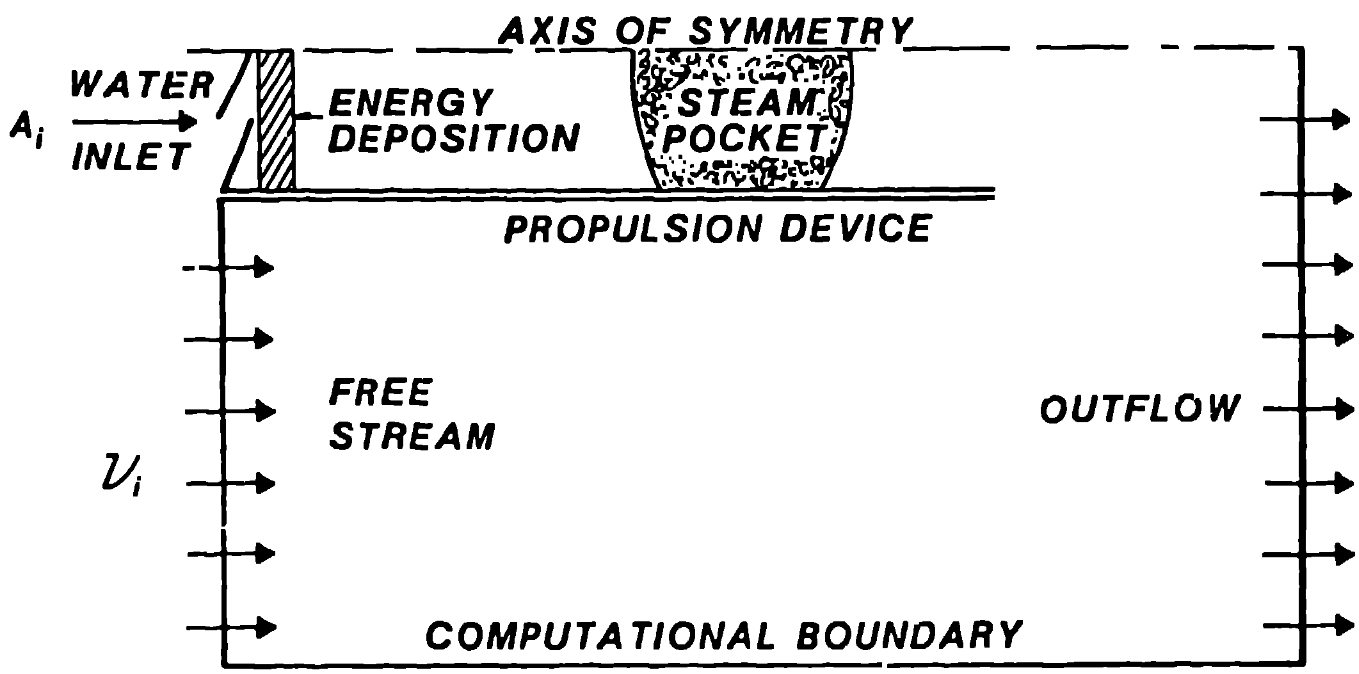


FIG. 3 COMPUTATIONAL REGION

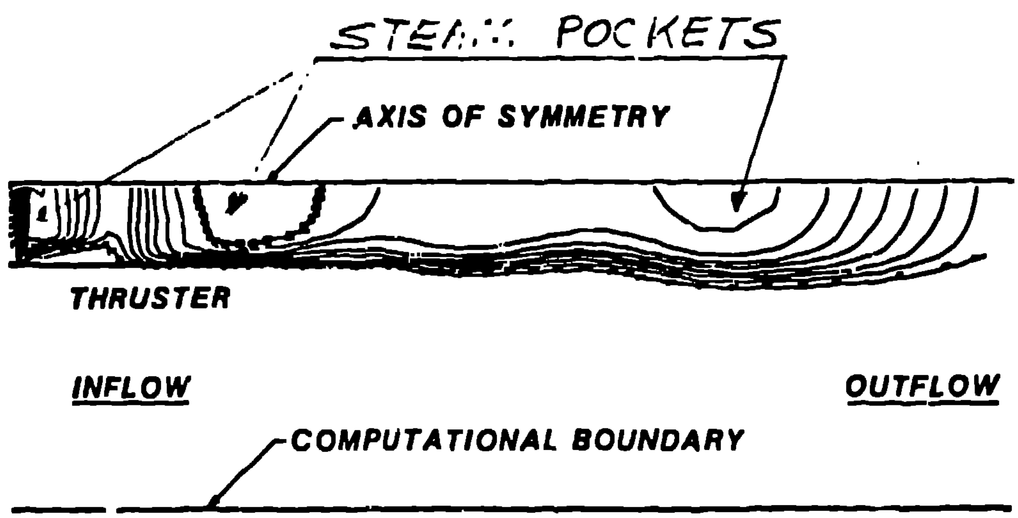
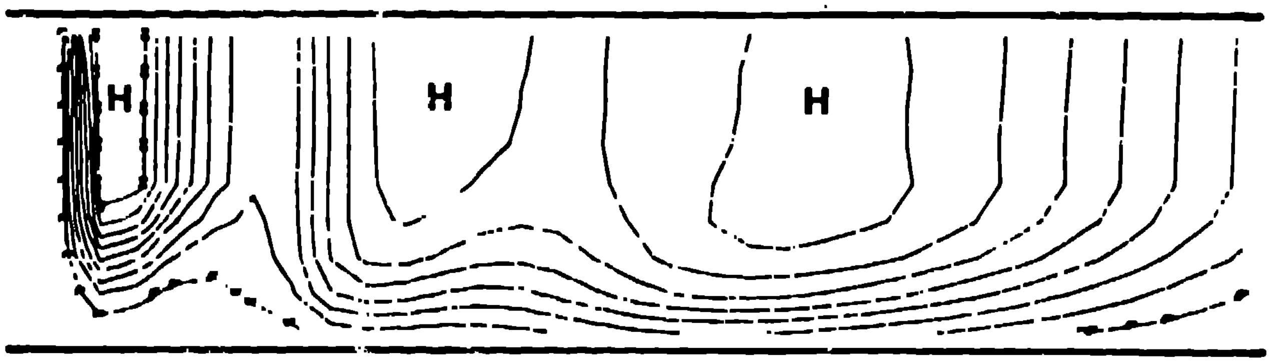


FIG. 4 CONTOURS OF CONSTANT VOID FRACTION



t=0.775s

FIG. 5 INTERIOR FLOW DETAIL (CONTOURS OF CONSTANT VOID FRACTION)

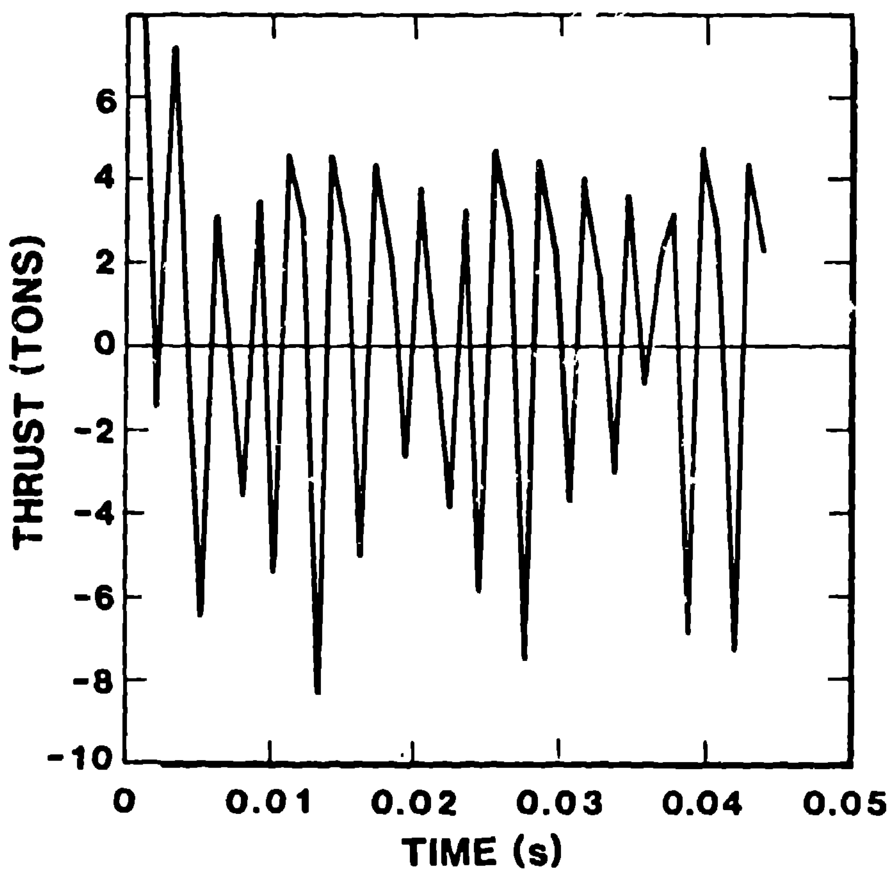


FIG. 6 INSTANTANEOUS THRUST
DEVICE DIA = 10 cm
(1 TON = 10^9 DYNE)

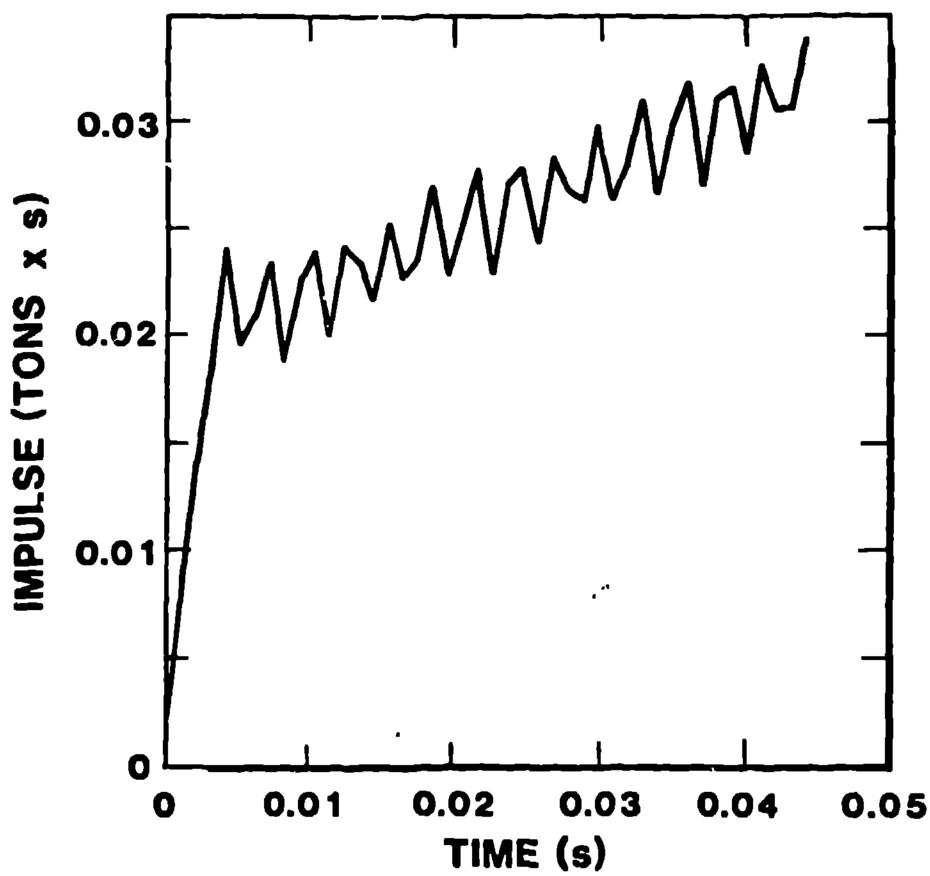


FIG. 7 IMPULSE
DEVICE DIA = 10 cm
(1 TON = 10^9 DYNE)

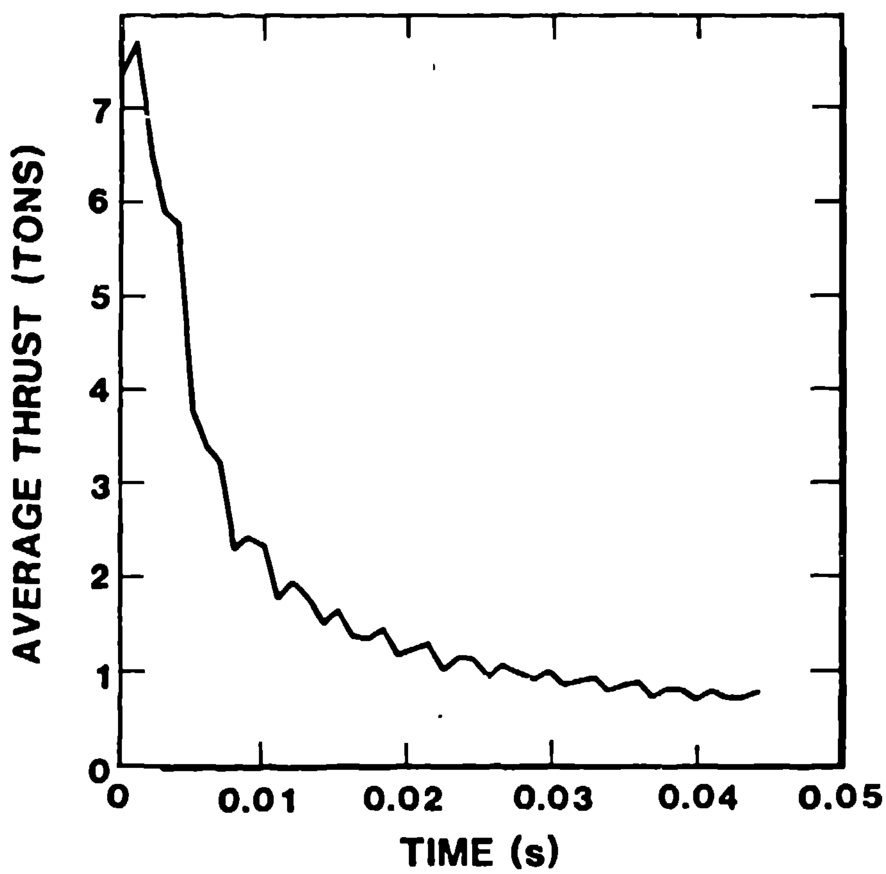


FIG. 8 AVERAGE THRUST
DEVICE DIA = 10 cm
(1 TON = 10^9 DYNE)

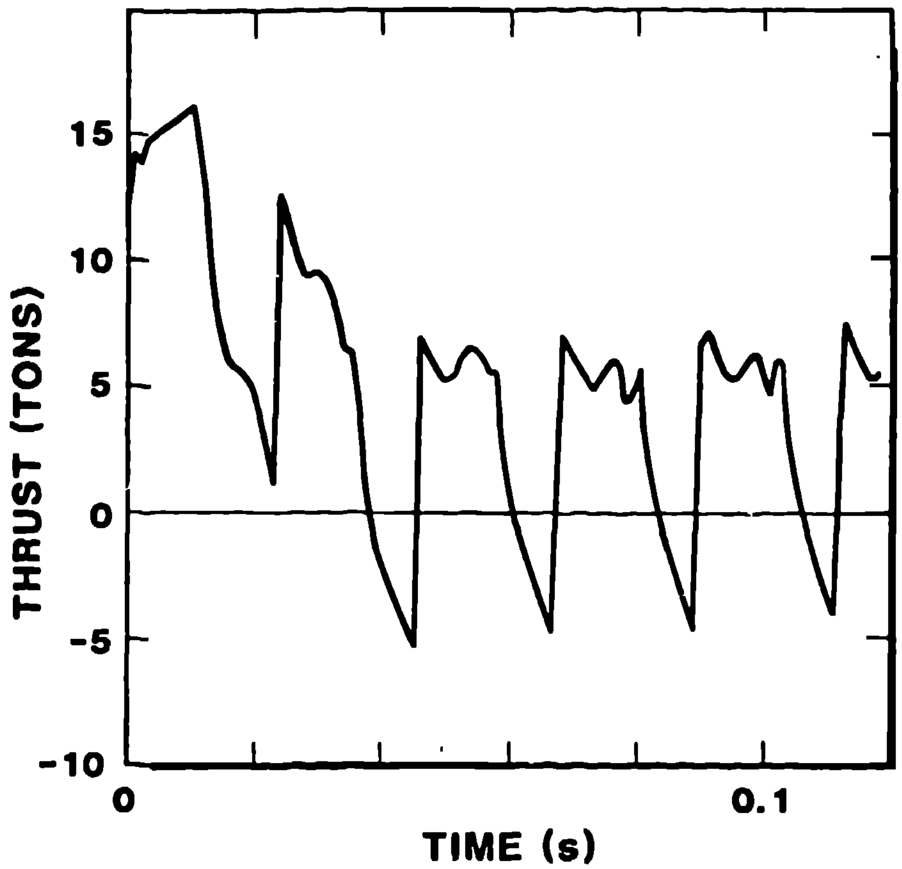


FIG. 9 INSTANTANEOUS THRUST
DEVICE DIA = 50 CM
(1 TON = 10^9 DYNE)

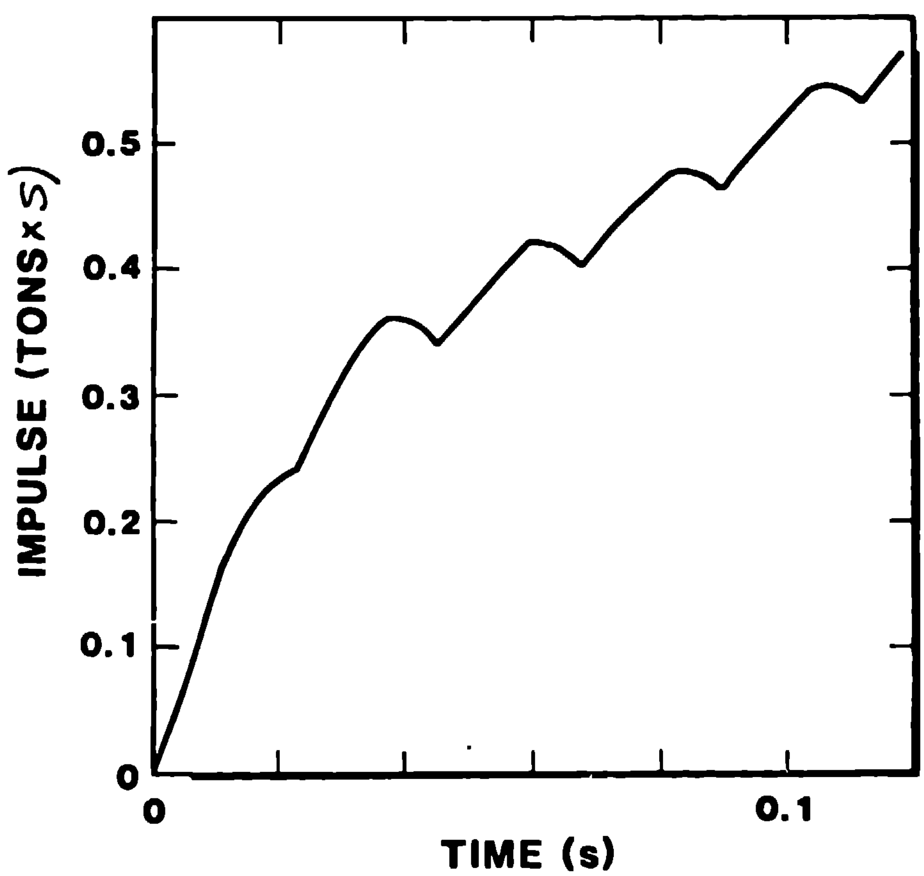


FIG. 10 IMPULSE
DEVICE DIA = 50 cm
(1 TON = 10^9 DYNE)

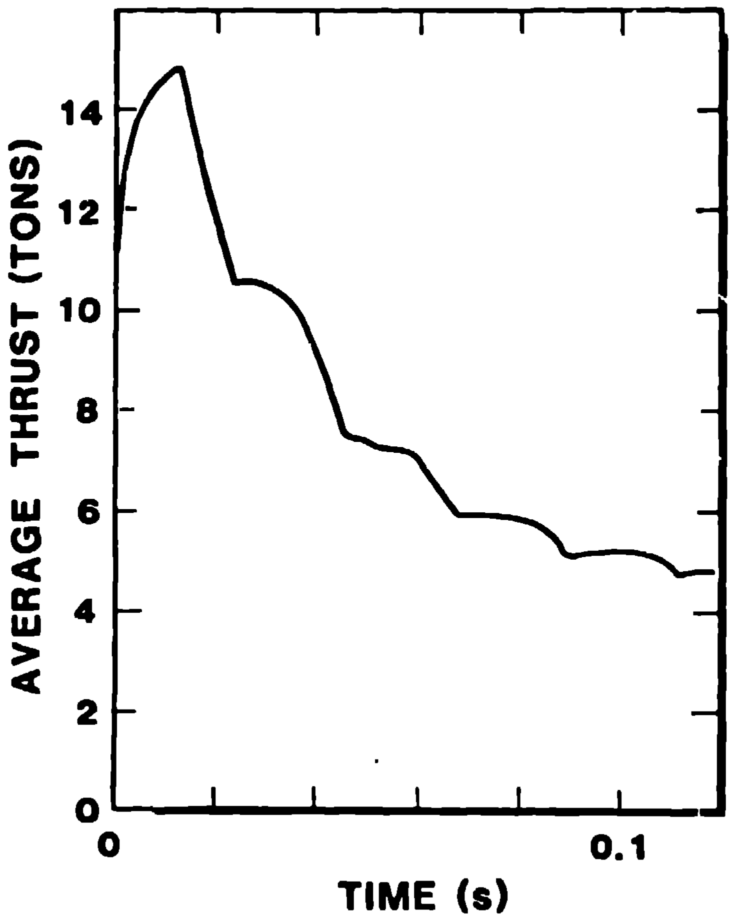


FIG. 11 AVERAGE THRUST
DEVICE DIA = 50 cm
(1 TON = 10^9 DYNE)

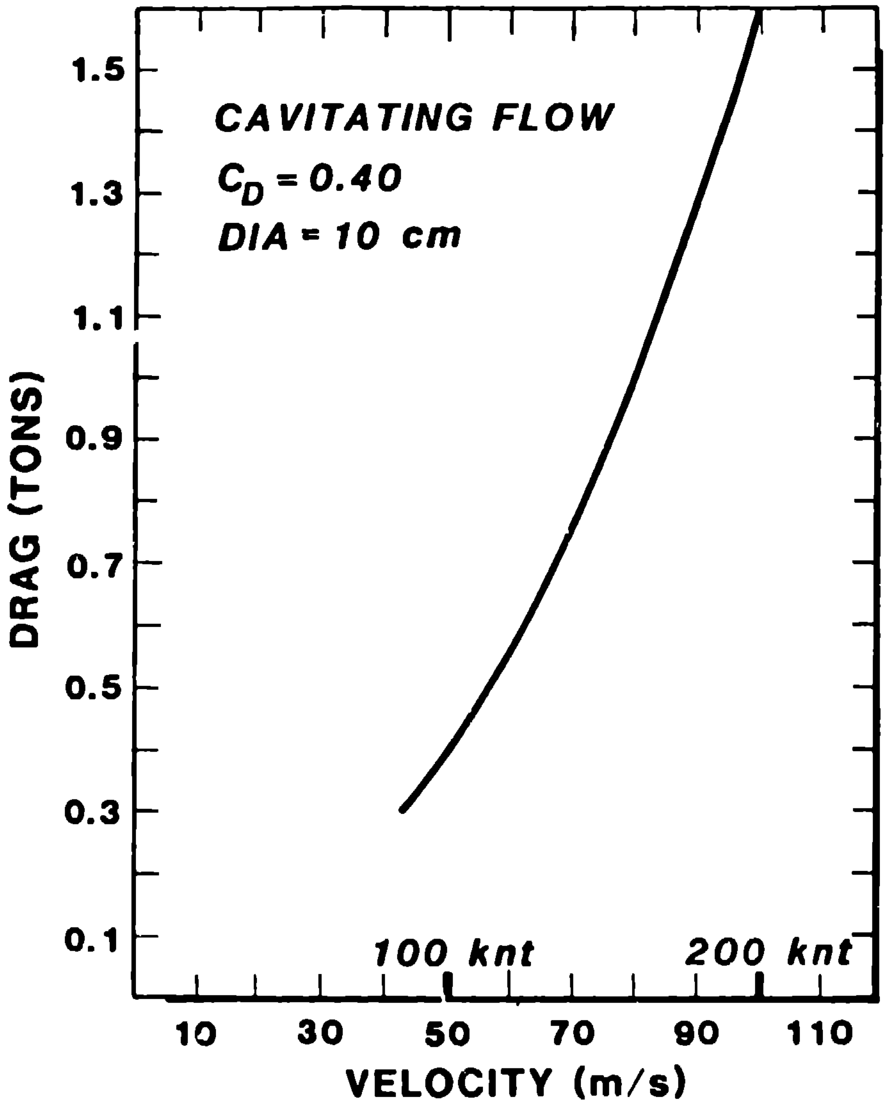


FIG. 12 THE DRAG OF THE 10 cm DIA PROJECTILE IN THE CAVITATING FLOW (1 TON = 10^9 DYNE)

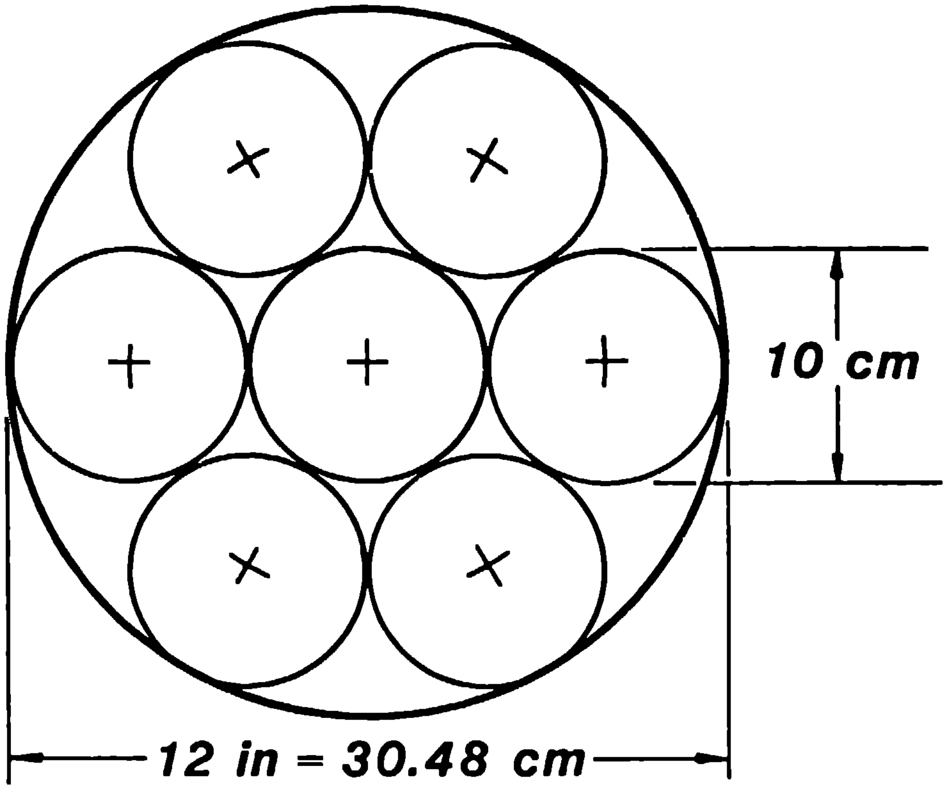


FIG. 13 ARRANGEMENT OF SMALL INDEPENDENTLY PROPELLED PROJECTILES INSIDE THE 12" ENVELOPE

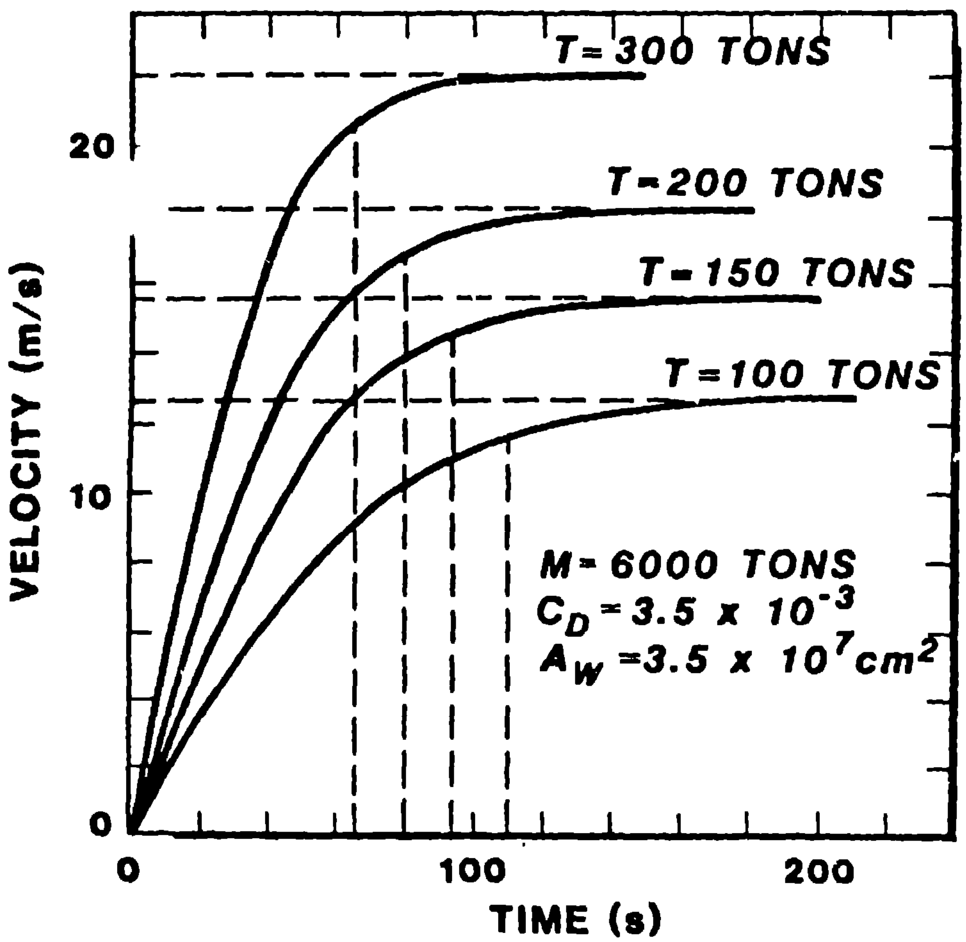


FIG. 14 ACCELERATION OF A 6000 TON VESSEL